# A Comparison of Future Weather Created from Morphed Observed Weather and Created by a Weather Generator

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To allow building scientists and engineers to investigate how their building designs fare in future climates there is the need for future weather files on an hourly time scale, which are representative of possible future climates. With the publication of the most recent UK Climate Projections (UKCP09) such data can be created for future years up to the end of the 21st century and for various predictions of climate change by one of two methods: mathematical transformations of observed weather (morphing), or the use of a synthetic weather generator. Here current and future weather is created by both of these methods for three locations within the UK and their statistical signatures discussed. Although the potential to use both products to investigate the effects of climate change is clear, it is found that the use of UKCP09 climate change anomalies within the morphing procedure give an unrealistic representations of future temperatures both mathematically and physically, limiting its use.

Key words: Climate change, future weather, UKCP09, thermal simulation

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## 1. Introduction

There is unequivocal evidence that the climate is warming evident from observations in global average and air and ocean temperatures [1]. Globally, temperatures have increased 0.8 °C since the late 19th century and have risen by 0.2 °C per decade over the past 25 years. It is very likely that most of the warming has been caused by man-made greenhouse gas emissions with a predicted global temperature rise of 2.8 °C (4 °C) under the A1B (A1FI) SRES emissions scenario by the end of the 21st century [2]. However more recent work has suggested the warming trend is likely to be higher [3].

There is a risk of building failure even for modest projections of climate change, with overheating becoming an increasingly important issue. There has been much recent interest in how buildings might perform in future climates in terms of thermal comfort and changes in energy use. The vast majority of this work has used regional or global climate models to investigate the impact on the urban environment. For example Wana et al investigated the projected changes in heating and cooling loads for five climatic regions in China using regression based models and applying these to global circulation models [4]. However the vast majority of work has used the climate models as anomalies to transform hourly observations [5,6,7,8]. A separate approach is to use a stochastic weather signal to produce data for use in building models. Although these were initially used to provide weather data in regions where there was a lack of observations [9], more recently they have been developed as a tool to easily incorporate climate change information into the observations [10].

In the UK, the release of the most recent climate projections, (UKCP09) present an opportunity not only for building simulation experts and architects and their clients, but for society as a whole. Unlike the previous climate data (UKCIP02) produced by the UK Climate Impacts Programme [11], the UKCP09 projections are probabilistic in nature [12]. UKCP09 has been produced to capture this uncertainty by including the natural climate variability, modelling uncertainty and future emissions [13]. This uncertainty is presented as probabilistic climate change projections. These projections give the relative likelihood of different future outcomes for key climatic variables such as temperature and rainfall. As part of UKCP09 a number of products have been released including projections of climate change over land on a 25 km grid and weather generator simulations on a 5km grid.

The release of UKCP09 allows the estimation of future weather for use in the built environment in a number of ways. In the UK, future weather years, as currently distributed by CIBSE [14], have been created using the morphing methodology of Belcher [15] where current observations are transformed using climate change anomalies associated with climate change. This method is simple to employ and using UKCP09, probabilistic weather years can be created for a range of emissions scenarios and time slices. However, although the change factors are available on a 25 km grid over the entire UK, there are limited observations from which to morph. UKCP09 also contains a weather generator which is able to output both daily and consistent hourly weather data on a 5 km grid over the UK for the historic period (1961-1990) and future time slices in decadal steps up to 2080 [16]. In this case many thousands of historic and probabilistic future weather years can be created; removing the limitation of a lack of observations. However, only a few variables are output, namely precipitation, dry bulb temperature, partial vapour pressure, relative humidity, sunshine fraction, total radiation and potential evapotranspiration. Inter-variable relationships that have been found from the underlying historic observations are maintained in the future weather, similar to the morphing process. This inevitably maintains the coincidence of weather patterns, which we currently observe. This is true for both methods of creating future weather series' considered in this paper.

There has been much research into how to produce representative future weather files from UKCP09 [17-21] of which a good overview has been provided by Mylona [22]. Although the majority of this work has investigated future climates produced by the weather generator CIBSE has indicated that it is interested in producing and developing morphed weather files for distribution across the UK. In this work the two methods for creating weather files will be compared namely via morphing and via the weather generator. This will be achieved by first comparing the weather generator control climate signal (representing 1961 to 1990) to observations of the same period. Secondly the applicability of the morphing procedure with UKCP09 change factors will be tested. Thirdly the morphed weather years will be compared to reference years generated from the UKCP09 weather generator. It is shown that both methods provide example weather files which are comparable. However, limitations to the applicability of the morphing procedure for the UKCP09 dataset and the benefit of the extra spatial resolution within the weather generator allows for more appropriate weather files to be created and thus more appropriate climate change adaptations to be considered from the weather generator.

## 2. The UKCP09 Weather Generator

UKCP09 includes a stochastic weather generator, which can create statistically plausible synthetic weather on an hourly or daily basis at a 5 km resolution consistent with the underlying climate projections [16]. The weather generator starts from well-established statistical relationships between observed climatic variables. The climate projections are then used to stretch these relationships to produce future time series on a daily and hourly basis. The weather signal itself is based around a stochastic rainfall model, which simulates rainfall sequences [23]. Other weather variables are then generated from the rainfall state. Five rainfall states are considered within the weather generator, these are; dry today/dry yesterday, wet today/wet yesterday, dry today/wet yesterday, wet today/dry yesterday and dry today/dry yesterday /dry day before. The use of the three-day dry sequence allows for the prediction of heat waves.

The weather generator outputs nine variables for the daily signal, which are the daily precipitation, maximum temperature, minimum temperature, sunshine fraction, vapour pressure, relative humidity, direct radiation, diffuse radiation and potential evapotranspiration (*PET*). Where as the hourly signal contains the variables hourly precipitation, temperature, vapour pressure, relative humidity, sunshine fraction, diffuse radiation, direct radiation. However, to create a weather file, the variables of wind speed, wind direction, air pressure and cloud cover need to be generated in a consistent manner with the rest of the weather signal. A method for producing the missing variables consistent with the rest of the weather signal has been described elsewhere, for more details see Eames et al [17] [24].

## 3. Comparison between the weather generator and observations

Before the weather generator can be used to predict future weather, first its ability to reproduce the base climate must be examined. The weather generator estimates the rainfall statistics using the Perry and Hollis gridded precipitation dataset [25]. This dataset interpolates observations on a 5 km resolution across the UK taking into account factors such as distance to the coast and the elevation. The other variables are then generated from the inter-variable relationships as observed at a network of 115 stations across the UK. The baseline climate for these datasets is from 1961 to 1990 for the rainfall statistics and 1961 to 1995 for the inter-variable relationships of daily data to account for the fraction of missing data. For the inter-variable relationships for hourly data a reduced network of 35 stations were available and the base period of 1961to 1995 is used to ensure at least 10 years' worth of data is included for all available sites. The rainfall model as used within the weather generator has been well tested previously and can be shown to predict the observed rainfall [23]. With respect to the built environment, rainfall mainly directly determines the likelihood of flooding at the location, and in terms of overheating has no relevance and hence the accuracy of such weather files for use in buildings depends on the success of the generation of the inter-variable relationships between themselves and the generated rainfall. Since the non-rainfall variables have no physical basis, although they are bounded by observed statistics, they are less robust than the rainfall model. The performance of these generated variables needs to be compared to the baseline climate before their use application within a thermal model can be recommended.

To test the UKCP09 weather generator's performance, the mean and standard deviations from the UKCP09 weather generator output for the control period hourly data are compared to the hourly observations for the same time period (1961-1990) [26]. The key parameters for modelling buildings which are available from the weather generator are the maximum temperature, minimum temperature, mean temperature, wind speed (calculated from *PET* with hourly values generated by the procedure described above) and solar irradiation as these variables drive heating energy, cooling energy and ventilation strategies. These variables will be investigated in turn. While it may seem self evident that the weather generator is able to statistically represent the observations on which it is based, the statistical nature of the disaggregation procedure, creating an hourly weather from the daily weather, which has a non-physical basis must be tested.

Figures 1, 2 and 3 show the observed and generated mean temperature, maximum temperature, minimum temperature and wind speed for the locations Plymouth, London and Edinburgh respectively. For each location 30 years of observations are used (1961-1990) and 3000 years from the weather generator. For each variable and each location the distributions of the observations match the distributions generated by the weather generator both in terms of the mean and the standard deviation. The largest differences are found to be in the calculation of the wind speed, with the greatest differences found in London and Edinburgh, where also the standard deviation for the weather generator is found to be much greater especially in the winter months. The largest difference for the maximum, minimum and mean temperature is found to be 0.8 °C, 0.7 °C and 0.5 °C respectively for Plymouth, 0.8 °C, 0.7 °C, 0.5 °C respectively for London and 0.8 °C, 0.8 °C and 0.5 °C respectively for Edinburgh. However the graphs demonstrate that the weather generator can model the weather at a location accurately in terms of minimum, maximum and mean temperature as well as the wind speed on an hourly basis and by further statistical analysis, the differences have been found to be insignificant by the use of T-Tests at the 5% level. Further validation of the weather generator has been carried out elsewhere [16].

Within the weather generator the solar radiation (direct and diffuse horizontal) is calculated as a daily value from the total sunshine duration and day of the year. This value is then disaggregated to produce hourly values. These calculations along with a limited number of observations make the comparison of solar radiation difficult. Previous work by Muneer has shown that the weather generator as first released with UKCP09 was unable to predict the observations for key climate variables including the sunshine duration and solar irradiation [27]. In the subsequent version (weather generator version 2) modifications were made to the sunshine hours as well as corrections to the baseline sunshine statistics. In this work it is these corrections which are investigated. Extensive validation has previously been carried out by UKCP09 to test the ability of the weather generator to predict the observed sunshine on a bimonthly basis [12] (see weather generator technical notes). This is not true for the irradiation values on a monthly and hourly basis and the sunshine on an hourly basis. To test whether the weather generator matches the observations, firstly the observed solar duration will be compared to the weather generator's solar duration, secondly the observed solar irradiance needs to match that produced by the weather generator, and finally, the hourly profile of solar irradiance of both observations and the weather generator are required to have the same distribution. For simplicity three locations are considered for this analysis: Camborne (50.23N / 5.33W), London (51.48N / 0.45W for sunshine duration, 51.47N / 0.31W for irradiation) and Belfast (54.66N / -6.22) [26].

Figure 4 shows the average sunshine duration (hrs), global irradiation ($kWhm^{-2}$), both observed and from the weather generator for Camborne, London and Belfast. Observations are from the period 1960 to 1995 and compared to 3000 years from the weather generator. For Camborne the weather generator under-predicts the amount of sunshine for all months with the largest absolute differences found in April (42 minutes), May (44 minutes) and August (40 minutes) but on average under-predicts the observations by 22 minutes. For London the largest absolute difference is found in August (24 minutes) but overall only under-predicts the observations on average by 4 minutes. For Belfast the largest difference is in May (54 minutes) but under predicts the average observed sunshine hours by 10 minutes. This implies that the weather generator on average will over predict the amount of cloud cover. However this has not aversely affected the mean monthly global horizontal irradiation. It is clear that the weather generator is able predict global irradiation for each month with the largest absolute difference found in March and December for Camborne with an overall difference of just 1%. For London the weather generator is found to overestimate the global irradiation with the largest differences found in January (15%) and December (14%) but overestimates the global irradiation over the whole year by 7%. For Belfast the weather generator has a tendency to under predict the total global irradiation with the largest difference in May (7 %) but only under predicts the yearly global irradiation by 1%. This demonstrates that the use of the weather generator can be justified on both a monthly and yearly time scales as the differences are small.

Figures 5, 6 and 7 show the average hourly sunshine duration for the months of January, April, July and September for Camborne, London and Belfast respectively. In this case hourly observations are available from 1982-1995 and are compared to 3000 years from the weather generator. The distribution of hourly sunshine has less agreement with observations than that found on a monthly timescale. While the total number of sunshine hours is similar as shown by figure 4, there are clear differences in the distribution of sunshine at the hourly time scale. Within each month the weather generator systematically predicts longer sunshine duration early in the morning and later in the afternoon but under predicts the sunshine duration in the middle of the day. However, the largest difference is 9 minutes for Belfast and 13 minutes for both London and Camborne. The differences between the observed and weather generator distributions become even more apparent when looking at the hourly average irradiation for June as shown by figure 8. At the beginning and end of the day (sunset and sunrise), the global irradiation for the weather generator, is composed of an average of 85 % direct irradiation on average compared to around 15 % found from observations. This is a very big difference and can be as high as 100 % direct irradiation in June (with a maximum of the order of 400 $Whm^{-2}$) and is generally caused by a day with very little sunshine in the winter and nearly a full day of sunshine in the summer. By inspection of the data, the largest error occurs when the daily sunshine hours is large (order of 16 hours in June). The disaggregation procedure produces full sun between sunshine between sunrise and sunset. However the diffuse radiation is disaggregated to between 7 am and 4 pm while the direct is disaggregated to between 4 am and 7 pm. As this discrepancy is an artefact of the disaggregation procedure only Camborne is displayed. The same artefact is found for every location and every 5km grid square and the majority of days. This artefact is an unphysical situation as these times are dominated by diffuse irradiation as shown by the observations. For example when the sun sets in an evening diffuse radiation is still present and by definition there is no direct radiation. Even when the sunshine duration is relatively large, the solar altitude at these times is not large enough to produce a large direct irradiation component as found by observations.

This discrepancy is due to the way in which the hourly sunshine is created within the weather generator. The daily total is first calculated using a model intended for the calculation of average daily solar radiation (direct and diffuse) [28]. These daily values are then disaggregated into hourly values using inter-variable relationships from observations whilst conserving the daily totals. This procedure puts a direct limitation on the radiation in any given hour. Thus the distribution of sunshine has only a statistical rather than a physical basis. A simple option could be to remove the instances of solar radiation at the beginning and end of the day. However as figures 4 and 8 show, the global and direct solar irradiation is under predicted by the weather generator and this would only increase this difference. As an alternative one could use the cloud cover each hour (as calculated using cloud cover = 1 - sunshine fraction [16]) and time of year within an hourly radiation model, namely the Cloud Radiation Model [29]. Originally this model was produced to estimate solar radiation at a location as the distribution of cloud cover observations is much more widespread than that of the solar radiation. Incidentally, it is this Cloud Radiation Model that is used to produce the solar radiation for the CIBSE reference years as currently distributed in the UK [30]. If within the weather generator the solar irradiation was not calculated at all on the daily or hourly time scale i.e. it wasn't disaggregated from the daily values, this would not be a problem and a model would simply be proposed to create hourly solar irradiation consistent with the other weather variables. As it stands the current data is unphysical and unrealistic for use in buildings models.

The calculated hourly average solar irradiation using the Cloud Radiation Model for June is shown in figure 9 for Camborne. The calculated distribution of solar irradiation matches the observed distribution around sunrise and sunset with the diffuse irradiation equalling the global irradiation. However at midday, there are differences. The direct component is smaller than the diffuse component whereas the observations predict that the components should be on average equal to each other. This is due to the reduction in the predicted sunshine within the weather generator at midday as shown by figures 5, 6 and 7. Furthermore table 1 shows the average total daily irradiation each month (global, diffuse and direct) for both the weather generator and that from the Cloud Radiation Model for Camborne. It is found that for each month there is very little difference between the two methods, with the total difference over the whole year of less than 1 %. Since the hourly solar irradiation distribution is improved while maintaining the monthly and yearly totals using the Cloud Radiation Model in comparison to the weather generator disaggregation procedure, it seems prudent to recalculate the solar radiation on an hourly timescale with an hourly solar model, namely the Cloud Radiation Model. Given that the observed weather is similar to the control output from the weather generator, the use of the weather generator to predict example future weather can be justified.

**4. Creation of Future Weather Years**

Previously, the performance of buildings under a changing climate has been studied using UKCIP02 predictions for changes to mean climate [11] (change factors) combined with CIBSE/Met Office weather years via a procedure commonly known as morphing [14]. The outputs of UKCP09 provide two options for the production of future weather; either adjusting observed weather with change factors in a similar method to that with UKCIP02 or sorting the hourly stochastic weather series from the weather generator into example weather years. UKCP09 provides change factors for three emission scenarios; low, medium and high, all decades between the 2020s and 2080s with a 25 km grid resolution (5 km for the weather generator, although, there is no further climate change signal than that of the 25 km square at the same location). The key difference between the two sets of projections is the use of probabilistic information within UKCP09. For each location (25 km grid square), decade and emissions scenario, 10,000 equi-probable realisations have been provided with the new projections [12]. This makes the creation of future weather files more complicated than using UKCIP02 as many future weather years can be realised from the vast number of possible change factors available. Similarly the weather generator, for each run, randomly samples from the 10,000 change factors available and creates a stationary 30-year time series. For one hundred runs this gives an hourly time series of 3000 future weather years in total. In either case an appropriate method for the selection of change factors is required either directly for the morphing procedure or indirectly from the generated time series from the weather generator so that the two methods can be fairly compared.

A method for producing future weather years from the weather generator has been proposed by Eames [17]. In this method the natural variability is sorted by finding an average year for each sample from the weather generator. This gave a total of 100 average years or Test Reference Years with each having a separate climate signal. The climate change signal is then ordered by finding the mean monthly temperatures and ordering them from lowest to highest. A 50$^{th}$ percentile year is produced by combining the 50$^{th}$ percentile January with the 50$^{th}$ percentile February and so on. This method gives a description of the future climate where by, for the 90$^{th}$ percentile year, it is unlikely to be greater than the temperature produced for the entire year and likewise for the 10$^{th}$ percentile year it is unlikely to be less than the temperature produced for the given emissions scenario and time slice.

To produce morphed weather files a very similar procedure can be employed. In this case the 10,000 monthly change factors are ordered by change in monthly temperature. To produce a 50$^{th}$ percentile year, the 50$^{th}$ percentile mean change in temperature for January is combined with the 50$^{th}$ percentile mean change in temperature for February and so on. This sample is then combined with a representation of an average weather year or Test Reference Year, in this case from observations from 1961 to 1990 to produce a representation of the future climate.

Ideally the methodology used to produce 10,000 change factors would create joint probabilities between all future variables, at all locations, at all future time periods so that relationships between all change factors can be investigated. However this calculation was not computationally feasible so the data was split into 2 batches. The first batch contains all variables relating to temperature (maximum temperature, minimum temperature, mean temperature, precipitation, cloud cover and relative humidity) while the second batch contains the rest (mean sea level pressure, specific humidity, net downward surface long wave flux, total downward surface long wave flux and net shortwave flux). Unfortunately robust joint probabilities can only be produced for variables from the same batch. This limits the number of variables that can be used within the morphing process. Thermal models do not necessarily require change factors for all weather variables but do require the weather variables to be consistent with each other. Since no joint probability can be achieved between any of the variables across both batches, the variables mean sea level pressure, wind speed, wind direction remain unchanged under the morphing procedure. However, in the UK, as the solar irradiance included in the current reference weather years is inferred from the cloud cover using the Cloud Radiation Model, as described above, the future solar irradiance can also be inferred from the change in cloud cover. As there are no probabilistic change factors for wind speed or wind direction the wind field is left unchanged from the historic weather under the assumption that the underlying weather pattern will remain constant. However when the morphing procedure was first proposed only a single description of climate change was available for each emissions scenario and time slice. With so many change factors available with a reduced number of variables used in the morphing procedure, the applicability of the morphing procedure must first be established.

The morphing procedure uses a number of mechanisms to transform the observed weather into future weather. These are a shift of the current weather by an amount equal to the absolute monthly mean change, a stretch by scaling it with the predicted relative monthly mean change or a shift and stretch combined. The latter is used for the change in dry bulb temperatures in order to integrate predicted variations of the diurnal cycle. Previously the first two procedures have been found to give an acceptable transformation of the underlying weather variables into a climate change signal. However, the stretch and morph of the temperature signal preserves the change in mean temperature and the diurnal cycle but not the change in maximum temperature and minimum temperature independently [13]. At the time (for UKCIP02 projections) this was deemed acceptable since the changes in maximum temperature and minimum temperature were not large and for each scenario only one projection was made available [11]. However, for the UKCP09 dataset this method is no longer appropriate due to the large number of samples available. To demonstrate this, the observed test reference year of Plymouth (for the 1961 to 1990 period) will be used in conjunction with the 2080, A1FI sampled data to produce morphed weather data. For simplicity only the month of August will be shown but the results equally apply to all months. Figure 10 shows the morphed average monthly maximum temperature against the expected future average maximum monthly temperature. The morphed average maximum temperature is calculated by taking the observed average maximum temperature for August and applying the standard morphing equation and the expected average monthly maximum temperature is calculated by adding the observed average maximum temperature for August to the projected change in the maximum temperature for all 10000 samples. Note the projections have been truncated at the 1 % and 99 % level [12]. Also displayed is the expected line where both methods produce the same future maximum temperature. The scatter from this line is quite significant and the average absolute difference is found to be 1.54 °C with the largest absolute difference is 8.71 °C. The morphing procedure is most accurate when the projected change in minimum temperature, maximum temperature and mean temperature are all-comparable which is a very small subset of the complete dataset. The applicability of this morphing procedure is therefore reduced.

There are two further problems of using the morphing procedure shown by figure 11. Figure 9(a) shows the absolute mean and coincident absolute maximum temperatures for each sample and figure 9(b) shows the absolute mean and coincident absolute minimum temperature for each sample. In each case the sampled data is ordered by the absolute mean temperature. Although for the majority of the data the mean temperature is higher than the minimum temperature and the maximum temperature is higher than the mean temperature, there are clearly many points where this is not true and on other occasions it is practically the same. This is issue arises when the mean (minimum) temperature change is greater than maximum (mean) temperature change to the extent it more than offsets the observed climatological difference between the observed maximum (mean) temperature and mean (minimum) temperature. This is because when the sampled data was produced, the method used meant that samples of maximum and minimum temperature are practically independent of samples of the mean temperature, when really they should be more strongly correlated. A stronger correlation would be expected such that if a low value of maximum temperature is sampled then a low value of mean temperature is sampled and similar for the minimum temperature, thereby maintaining the observed climatology. These issues are not restricted to just this location and this month and is therefore an issue for the original morphing methodology for this dataset. It should be noted however, that this does not affect the weather generator as it only samples from the mean temperature and infers the maximum and minimum temperatures using empirical relationships from observations.

Due to the numerous problems of the sampled data detailed above this leaves two options for using the UKP09 dataset to morph observed temperature data. Firstly it is possible to develop relationships between mean temperatures and the minimum and maximum temperatures from the data released from the regional climate model [12]. However the mean temperature changes and associated changes in other variables were developed within UKCP09 based on many climate models not just from the UK and thus the association with other climatic variables will not be robust. Furthermore the regional climate model was only run with the medium emissions scenario (a1b) limiting its use. The second approach is to treat the morphing of temperature as only a shift of the observed temperature by an amount equal to the absolute monthly mean change. Although this method would ignore any effect of potential changes in the relationship between maximum, minimum and mean temperature due to climate change, due to the errors highlighted with the projections it is this shift which will be used to predict morphed temperature changes as it is the most straight forward to implement and will give the most robust solution. This method could also have further implications on the range of future predicted maximum and minimum temperatures where the range of change factors for the mean temperature is smaller than that of both the maximum and minimum temperature as is the case for Plymouth in the month of August. In this case it is unlikely that the most extreme temperatures would be accounted for.

**5. Comparison of Morphed and Generated Weather**

To compare the two methods for creating future example weather years, using the weather generator and the UKCP09 morphing procedure, three locations have been chosen; Plymouth, London and Edinburgh. These are three of the current 14 locations used for standard compliance modelling in the UK [14] and at these locations there is enough data such that reference years from the period 1961 – 1990 can be created from observations for a true comparison to the base period of the weather generator [26]. The 5km grid square in which the observation station is found is selected by the weather generator to reduce spatial errors.

Tables 2, 3 and 4 show the mean daily minimum temperature, mean daily maximum temperature, mean temperature, mean horizontal global irradiation and mean diffuse irradiation for the base climate (1961-1990) and three future periods (2030s, 2050s, and 2080s), for both the weather generator and morphing procedure, for three locations (Plymouth, London and Edinburgh) and three percentiles (10$^{th}$ percentile, 50$^{th}$ percentile and 90$^{th}$ percentile). The emission scenario in each case is the A1FI (high). The two methods result in a very similar time series of future and base climate. Both methods show that there is an increase in temperature, little change in the diffuse irradiation and an increase in the direct solar irradiation across the century as percentiles increase across the century. However, there are key differences between them. While the mean temperatures are similar between the two methods for all locations, percentiles and time periods, the maximum and minimum temperatures are not. For each location the morphing procedure systematically produces warmer minimum temperatures and cooler maximum temperatures. This is true for both the base period (where no morphing is applied) and the future periods. This could be due to the difference in the dataset used for each method, but under climate change some of the differences are due to a lack of a stretch in the minimum and maximum temperatures within the morphing procedure. Furthermore the weather generator, for each scenario the constructed weather file is composed from 3,000 statistically generated individual years where it has been previously shown that it is able to statistically represent the base climate in figures 1, 2 and 3. For the morphed scenarios only 30 years are used from observations to generate a reference year with change factors applied for each scenario to this same reference year. This reference year is based on the most average monthly temperature, cloud cover and wind speed and therefore does not necessarily contain any periods which are statistically representative of the entire climate so it is not surprising that there are some differences in these variables. Higher percentiles and later time periods have a tendency to increase these differences between the two procedures. It must be noted that the exact same weather patterns are produced by the morphing procedure which are stretched by the climate change anomalies, this is not true for the weather generator and each year produces a very different set of weather patterns.

Tables 2, 3 and 4 also show there are differences in the mean global and direct irradiation. This has been found to be due to the differences in cloud cover during daylight hours. The reduced cloud cover during the day increases the amount of direct irradiation and also the total global irradiation. While the analysis in the section above has shown that the weather generator is able to predict the observed global irradiation, the reference year procedure has a tendency to produce years whereby the year selected has a similar temperature to the morphing procedure, associated with lower coincident cloud cover.

**6. The use of future weather files within a thermal model**

Building simulation is common practice to test how a design might perform in reality or even to test the performance of retrofit solutions to existing constructions. In the case of future climates the use of building simulation can be used to test how climate proof the design may be. To test the two procedures for creating future weather years to see if there is any material difference between them, a school building has been studied for three locations (Plymouth, London and Edinburgh). The building conforms to UK 2002 Building Regulations. Full details of the construction can be found in the appendix. The model has been calibrated to typical annual heating and electricity consumption for such naturally ventilated buildings [32]. In this study only one building has been chosen as an example to highlight some of the differences between the two procedures to generate simulated weather when run through a building model.

Simulations were performed for the weather generator weather files and morphing procedure weather files for the base case, 2030 50$^{th}$ percentile, 2050 50$^{th}$ percentile and 2080 50$^{th}$ percentile. For the morphing procedure the base case refers to the 1961-1990 reference year from observations with no morphing applied. A number of metrics will be used to describe the internal conditions of the building. These are the mean internal summer temperature (outside the heating season), the total heating load, the number of occupied hours over 28 °C and the number of weighted cooling degree hours (WCDH) based on an adaptive thermal comfort temperature [32]. While the number of hours over a set temperature (28 °C in the UK) is a common metric used to determine the level of overheating within a building, it does not necessarily demonstrate the extent of the overheating and the stress to the occupants; for example four hours at 29 °C is as significant as four hours at 35 °C but the higher temperature is likely to cause more discomfort. However, the temperature at which the majority of people are uncomfortable has been found to vary with outside temperature, which will become more significant under climate change and a warming climate as people learn to adapt to warmer internal environments. The comfort temperature ($T_c$) is given by the equation

$$T_c = 0.33T_{rm,i} + 20.8 \ , \tag{1}$$

where $T_{rm,i}$ is the running mean outdoor temperature on day $i$ given by the equation

$$T_{rm} = (1-\alpha)\left(T_{rm,i-1} + \alpha T_{rm,i-2} + \alpha^2 T_{rm,i-3} \ldots\right) . \tag{2}$$

Where $\alpha$ is a constant, which in this case equal to 0.8 [33]. The WCDH is then given by the sum of the square of the difference between the comfort temperature and the internal temperature when the internal temperature is greater than the comfort temperature [34].

Tables 5 to 7 show that the building warms over the base climate under climate change using both the weather generator and the morphing procedures weather files in terms of mean temperature, occupied hours greater than 28 °C and WCDH for all locations. Similarly, the heating load is found to reduce over the same period. However in each case the internal thermal environment simulated using the weather generator files has a tendency to produce slightly warmer internal environments with differences between the two sets of weather files generally smaller for the base case. This is unsurprising from data in tables 2, 3 and 4 where it is found that average maximum temperatures are warmer for the weather files generated using the weather generator at each location, percentile and time period.

The trends in the warming of the building from using both sets of weather files are similar demonstrating that both methods could be used to investigate the effects of climate change. However the lack of a stretch of maximum temperatures in the morphing procedure would limit any investigation into overheating under climate change highlighted by the generally smaller number of occupied hours over 28 °C.

**7. Discussion and Conclusion**

In this work two methods to produce future design weather data from the climate projections UKCP09 are investigated; using a statistical weather generator and morphing of historical observations.

It is found that the weather generator is able to statistically produce weather data consistent with the historical observations in terms of wind speed, direct irradiation, diffuse irradiation, global irradiation, maximum temperature, minimum temperature and mean temperature on a monthly timescale as shown by figures 1–4. However, on an hourly basis there are clear issues with the distribution of the sunshine hours and the distribution of direct and diffuse irradiation leading to the impossible situation where the direct irradiation is on average greater than the diffuse irradiation at the beginning and end of the daylight hours as shown by figures 5 – 8. A simple model (The Cloud Radiation Model) was proposed to create hourly solar irradiance with the hourly weather generator data as this model is used to produce solar irradiance with hourly reference weather as currently distributed in the UK. This simple model was found to correct the differences between the distribution of observed and modelled weather as shown by figure 9 and table 1.

The second method to produce future weather files involves the transformation of an observed weather series using change factors associated with predicted changes in climate. The morphing procedure was initially used to transform observed weather using the climate change projections UKCIP02. In this case mean change factors were available for many weather variables for four emissions scenarios, three future time periods on a 50 km grid. For UKCP09, 10,000 sets of change factors were made available for three emission scenarios, for seven time periods on a 25 km grid. In this case due to the size of the dataset the variables were processed into two separate batches restricting the variables that could be transformed coincidently. So variables such as wind speed, wind direction and air pressure remain constant for all future scenarios. Likewise future solar radiation changes were inferred from the change in cloud cover using the Cloud Radiation Model. However, two further problems were found with the transformation of temperatures. The original morphing procedure used a shift and stretch to produce morphed temperatures to preserve the mean temperature and the change in the diurnal cycle. The errors were found to be small as the differences between the projected change in minimum, maximum and mean temperature were relatively small using UKCIP02. This however is not the case for the change factors within UKCP09 due to the large number of change factors available. Figure 10 shows that the projected changes in maximum, mean and minimum temperature are large so that the difference between the projected maximum temperature and the morphed maximum temperature can be as high as 8.71 °C. Furthermore figure 11 showed that the projected changes in mean temperature were large enough in some samples to overcome the climatalogical difference between the mean and maximum temperature (and similar for the minimum temperature). The only realistic method to simply transform the observed temperature series was found to be the use a shift by the mean temperature change only. Although projected changes in the maximum and minimum temperatures is unaccounted for it is the most robust solution for all emissions scenarios as the robustness of coincident maximum, minimum and mean temperatures is poor. This however, will have a knock on effect if considering the risk of overheating, as the data may not give a realistic representation of future condition and extreme temperatures are unlikely to be adequately represented.

Both sets of weather files were found to have similar mean temperatures for the locations studied (Edinburgh, London, and Plymouth) as shown by tables 2, 3 and 4. The weather generator weather files are found to consistently have cooler average minimum temperatures and warmer average maximum temperatures when compared to morphed weather files. Although there are clear structural differences between the two methods they both show the same underlying climate change signal with temperatures increasing across the century, increases in direct solar irradiation and little change in the diffuse irradiation. When placed through a model of a building the internal environment for weather files created by the weather generator are found to be generally warmer than that of the morphed weather files as shown by tables 5,6 and 7. This however, is to be expected given the origins of the data created. The predictions of the number of occupied hours over 28 °C and the weighted cooling degree hours is generally lower with the morphed weather files and could be a direct consequence of the lack of a stretch in peak temperatures and therefore its use within overheating analysis should be used with caution.

Both sets of weather data show potential for use within buildings models to investigate the response to climate change. However there are clear issues with the morphing procedure using UKCP09 and caution must be used when investigating the effects of extreme temperatures. Furthermore, locations are clearly limited to the distribution of historic weather stations. In this case the weather generator has a clear advantage of a much greater spatial resolution (on a 5 km grid) and the data carries no copyright allowing the data to be freely distributed to building professionals.

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## Appendix

Details of building construction.

| | |
|---|---|
| Building | School |
| Wall construction | Block/insulation/plasterboard/plaster |
| Glazing construction | Double glazed |
| Floor construction | Concrete/Insulation/chipboard/Carpet |
| Roof construction | Steel/insulation/plasterboard |
| Wall U-value ($W/m^2K$) | 0.35 |
| Glazing U-value ($W/m^2K$) | 2 |
| Floor U-value ($W/m^2K$) | 0.25 |
| Roof U-value ($W/m^2K$) | 0.25 |
| Floor area ($m^2$) | 887 |
| Storeys | 1 |
| Glazed fraction | 19% |
| Internal partitions | Block |
| Infiltration | 0.25 ac/h |
| Lighting gains $W/m^2$ | 13 |
| Other electrical gains $W/m^2$ | 2 |
| Occupancy $m^2$/person | 3.46 |
| Windows opening | 22 °C when occupied |

**Tables**

| | Global irradiation W/m$^2$ | | Direct irradiation W/m$^2$ | | Diffuse irradiation W/m$^2$ | |
|---|---|---|---|---|---|---|
| | Weather generator | CRM | Weather generator | CRM | Weather generator | CRM |
| Jan | 34 | 31 | 9 | 9 | 26 | 22 |
| Feb | 59 | 56 | 18 | 19 | 42 | 36 |
| Mar | 101 | 103 | 35 | 41 | 65 | 62 |
| Apr | 170 | 168 | 81 | 76 | 89 | 91 |
| May | 212 | 212 | 102 | 98 | 110 | 114 |
| Jun | 228 | 230 | 110 | 107 | 119 | 123 |
| Jul | 219 | 223 | 102 | 103 | 116 | 120 |
| Aug | 184 | 187 | 86 | 86 | 99 | 100 |
| Sep | 134 | 134 | 61 | 60 | 74 | 74 |
| Oct | 76 | 79 | 26 | 32 | 50 | 47 |
| Nov | 42 | 42 | 12 | 15 | 30 | 27 |
| Dec | 29 | 26 | 7 | 8 | 21 | 19 |

Table 1. Comparison between the average weather generator hourly solar irradiation and the solar irradiation calculated from the weather generator hourly sunshine duration, using the Cloud Radiation Model (CRM).

| | | Average Daily Min Temp °C | | Average Daily Max Temp °C | | Mean Temp °C | | Mean Global Rad Wm$^{-2}$ | | Mean Diffuse Rad Wm$^{-2}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | WG | M | WG | M | WG | M | WG | M | WG | M |
| Base | | 7.9 | 8.0 | 13.7 | 13.3 | 10.8 | 10.7 | 122 | 109 | 68 | 67 |
| 2030 | 10% | 8.5 | 8.7 | 14.3 | 14.0 | 11.3 | 11.4 | 123 | 109 | 67 | 67 |
| | 50% | 9.5 | 9.8 | 15.7 | 15.1 | 12.6 | 12.5 | 126 | 118 | 69 | 69 |
| | 90% | 10.8 | 11.0 | 17.0 | 16.3 | 13.8 | 13.7 | 128 | 114 | 68 | 68 |
| 2050 | 10% | 9.2 | 9.2 | 14.8 | 14.5 | 11.9 | 12.0 | 122 | 111 | 67 | 68 |
| | 50% | 10.3 | 10.6 | 16.6 | 16.0 | 13.4 | 13.4 | 130 | 119 | 68 | 69 |
| | 90% | 12.0 | 12.3 | 18.4 | 17.7 | 15.2 | 15.1 | 128 | 126 | 68 | 72 |
| 2080 | 10% | 10.0 | 10.1 | 15.7 | 15.5 | 12.8 | 12.9 | 128 | 120 | 67 | 69 |
| | 50% | 11.9 | 12.1 | 18.0 | 17.5 | 14.9 | 14.9 | 133 | 126 | 67 | 70 |
| | 90% | 14.1 | 14.6 | 20.9 | 20.0 | 17.4 | 17.4 | 135 | 126 | 66 | 71 |

Table 2. Key statistics for reference weather files for Plymouth

| | | Average Daily Min Temp °C | | Average Daily Max Temp °C | | Mean Temp °C | | Global Rad Wm$^{-2}$ | | Diffuse Rad Wm$^{-2}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | WG | M | WG | M | WG | M | WG | M | WG | M |
| Base | | 4.6 | 5.1 | 12.1 | 11.8 | 8.3 | 8.5 | 104 | 98 | 62 | 64 |
| 2030 | 10% | 5.2 | 5.7 | 12.7 | 12.4 | 8.9 | 9.2 | 107 | 97 | 62 | 63 |
| | 50% | 6.5 | 6.8 | 13.7 | 13.5 | 10.1 | 10.2 | 103 | 98 | 60 | 64 |
| | 90% | 7.5 | 8.0 | 15.2 | 14.7 | 11.3 | 11.4 | 107 | 104 | 61 | 65 |
| 2050 | 10% | 5.5 | 6.2 | 13.4 | 12.9 | 9.4 | 9.6 | 108 | 94 | 61 | 62 |
| | 50% | 7.0 | 7.6 | 14.8 | 14.3 | 10.9 | 11.0 | 105 | 103 | 61 | 65 |
| | 90% | 8.6 | 9.2 | 16.6 | 15.9 | 12.5 | 12.6 | 110 | 105 | 61 | 66 |
| 2080 | 10% | 6.4 | 7.0 | 14.2 | 13.7 | 10.2 | 10.4 | 110 | 98 | 61 | 63 |
| | 50% | 8.2 | 8.9 | 16.2 | 15.6 | 12.2 | 12.4 | 108 | 109 | 61 | 66 |
| | 90% | 10.8 | 11.3 | 18.5 | 18.0 | 14.6 | 14.7 | 115 | 106 | 61 | 65 |

Table 3. Key statistics for reference weather files for Edinburgh.

| | | Average Daily Min Temp °C | | Average Daily Max Temp °C | | Mean annual Temp °C | | Global Rad $Wm^{-2}$ | | Diffuse Rad $Wm^{-2}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | WG | M | WG | M | WG | M | WG | M | WG | M |
| Base | | 6.7 | 7.1 | 14.5 | 14.1 | 10.5 | 10.5 | 122 | 111 | 68 | 68 |
| 2030 | 10% | 7.2 | 7.8 | 15.1 | 14.8 | 11.1 | 11.3 | 123 | 111 | 67 | 68 |
| | 50% | 8.4 | 9.0 | 16.6 | 15.9 | 12.4 | 12.4 | 126 | 120 | 69 | 70 |
| | 90% | 9.6 | 10.3 | 18.2 | 17.2 | 13.8 | 13.7 | 128 | 122 | 68 | 70 |
| 2050 | 10% | 7.9 | 8.4 | 15.6 | 15.3 | 11.7 | 11.8 | 122 | 119 | 67 | 71 |
| | 50% | 8.9 | 9.9 | 17.7 | 16.8 | 13.3 | 13.3 | 130 | 115 | 68 | 67 |
| | 90% | 11.0 | 11.6 | 19.5 | 18.6 | 15.2 | 15.1 | 128 | 123 | 68 | 69 |
| 2080 | 10% | 8.8 | 9.2 | 16.2 | 16.2 | 12.5 | 12.6 | 128 | 112 | 67 | 67 |
| | 50% | 10.6 | 11.4 | 18.9 | 18.3 | 14.7 | 14.8 | 133 | 126 | 67 | 70 |
| | 90% | 13.4 | 14.0 | 22.0 | 21.0 | 17.6 | 17.4 | 135 | 128 | 66 | 68 |

Table 4. Key statistics for reference weather files for, London.

| | Mean internal summer temperature °C | | WCDH | | Heating load MW | | Occupied hours > 28 °C | |
|---|---|---|---|---|---|---|---|---|
| | WG | M | WG | M | WG | M | WG | M |
| Base | 20.8 | 20.3 | 2 | 2 | 37 | 40 | 0 | 0 |
| 2030 50% | 21.8 | 21.4 | 32 | 17 | 28 | 30 | 6 | 2 |
| 2050 50% | 22.6 | 22.0 | 67 | 43 | 24 | 26 | 14 | 9 |
| 2080 50% | 23.9 | 23.2 | 280 | 126 | 19 | 20 | 99 | 35 |

Table 5. School environmental data for Plymouth.

| | Mean summer temperature °C | | WCDH | | Heating load MW | | Occupied hours > 28 °C | |
|---|---|---|---|---|---|---|---|---|
| | WG | M | WG | M | WG | M | WG | M |
| Base | 21.7 | 21.2 | 278 | 152 | 40 | 40 | 25 | 18 |
| 2030 50% | 22.8 | 22.6 | 187 | 429 | 29 | 31 | 34 | 54 |
| 2050 50% | 23.9 | 23.2 | 977 | 670 | 27 | 27 | 120 | 84 |
| 2080 50% | 25.1 | 24.7 | 1159 | 1420 | 24 | 22 | 201 | 174 |

Table 6. School environmental data for London.

| | Mean summer temperature °C | | WCDH | | Heating load MW | | Occupied hours > 28 °C | |
|---|---|---|---|---|---|---|---|---|
| | WG | M | WG | M | WG | M | WG | M |
| Base | 19.7 | 19.6 | 13 | 13 | 52 | 48 | 0 | 0 |
| 2030 50% | 20.6 | 20.5 | 15 | 38 | 41 | 39 | 0 | 4 |
| 2050 50% | 21.3 | 21.1 | 35 | 65 | 39 | 35 | 5 | 6 |
| 2080 50% | 22.4 | 22.2 | 168 | 143 | 32 | 29 | 27 | 13 |

Table 7. School environmental data for Edinburgh.

**Figure Captions**

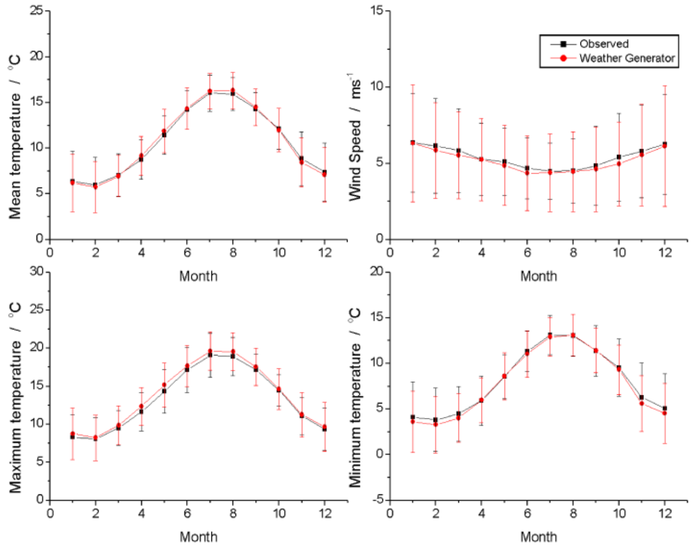


Figure 1. Comparison between the UKCP09 weather generator weather variables and observations for Plymouth. The mean for each month is displayed for both data sets and the extent of the first standard deviation.

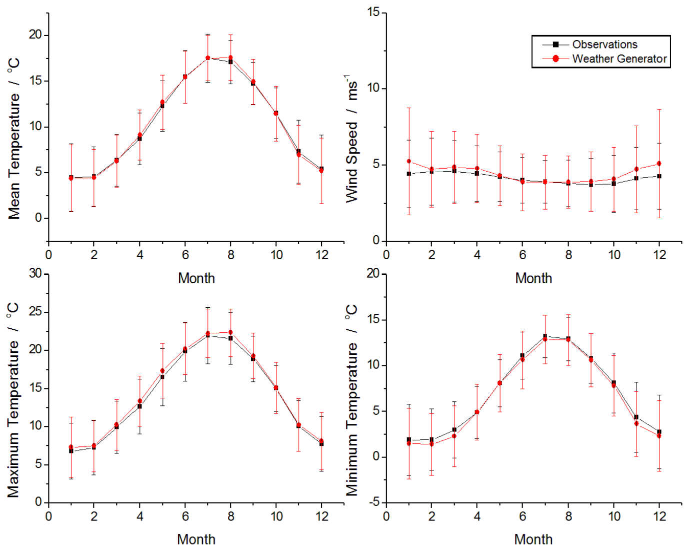


Figure 2. Comparison between the UKCP09 weather generator weather variables and observations for London. The mean for each month is displayed for both data sets and the extent of the first standard deviation.

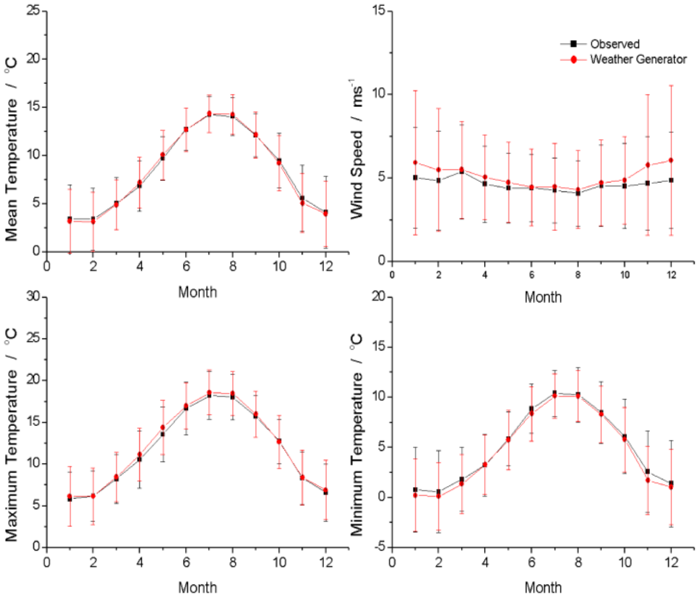


Figure 3. Comparison between the UKCP09 weather generator weather variables and observations for Edinburgh. The mean for each month is displayed for both data sets and the extent of the first standard deviation.

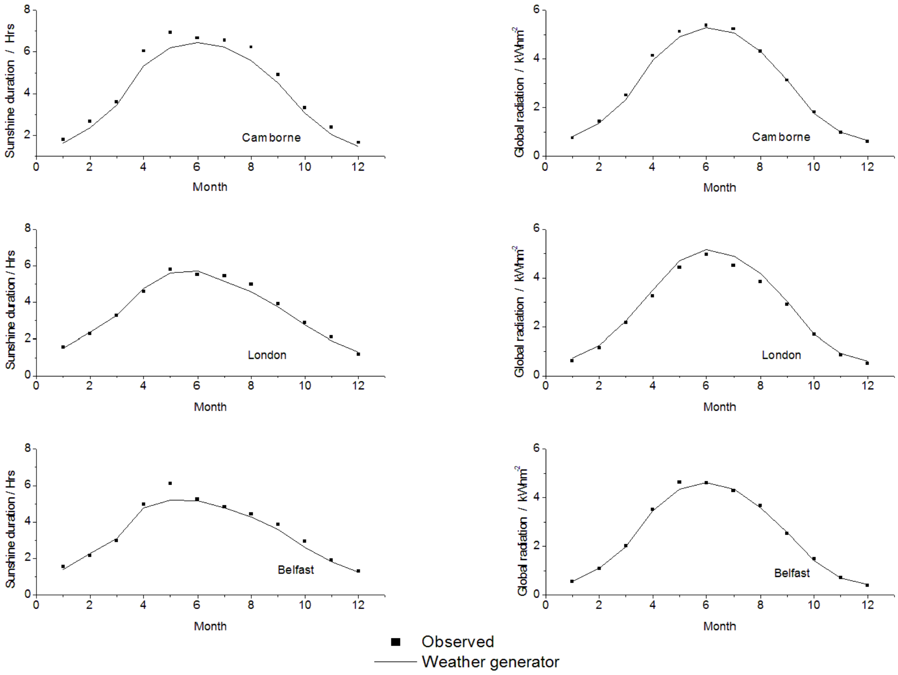


Figure 4. Comparison between the observed and weather generator sunshine duration and global radiation for Camborne, London and Belfast.

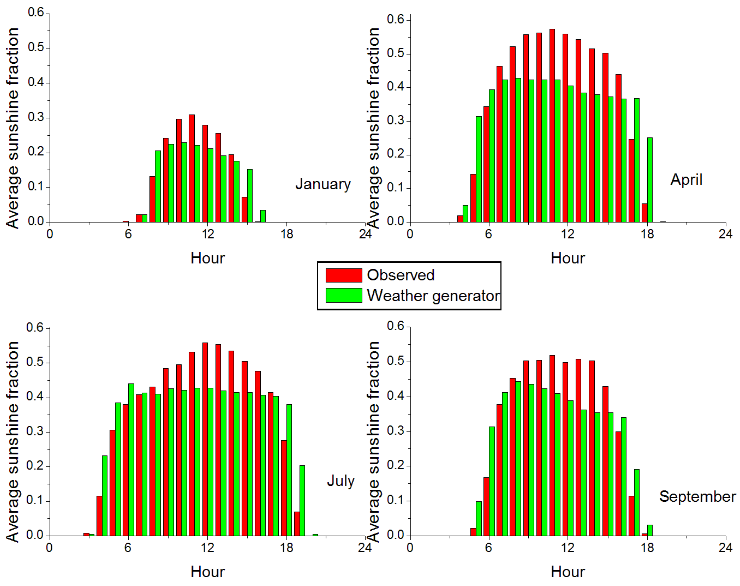


Figure 5. Average hourly sunshine duration for January, April, July and September for Camborne.

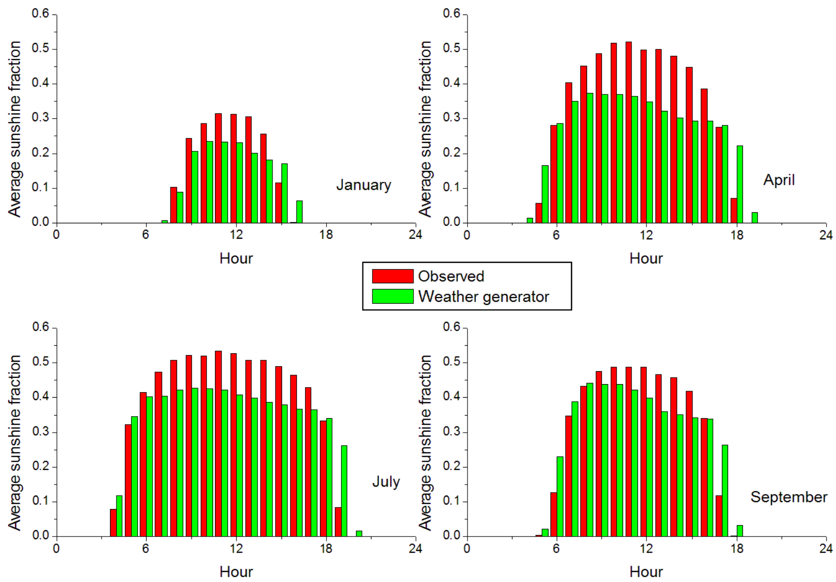


Figure 6. Average hourly sunshine duration for January, April, July and September for London.

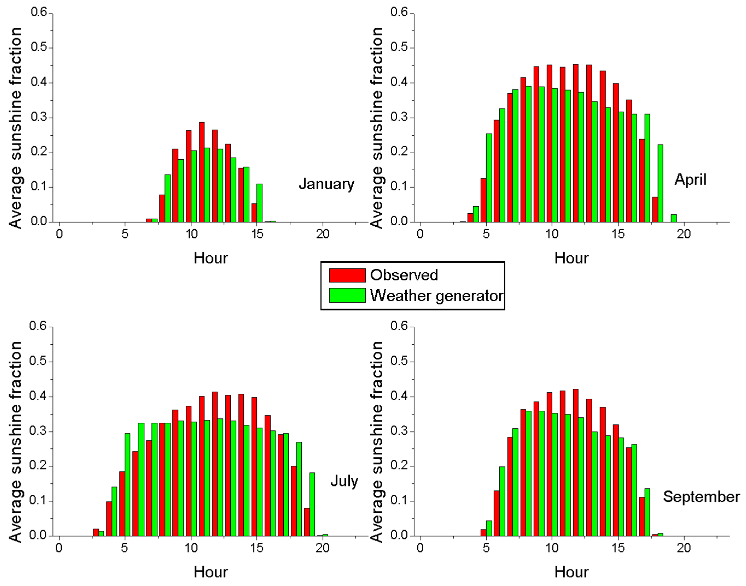


Figure 7. Average hourly sunshine duration for January, April, July and September for Belfast.

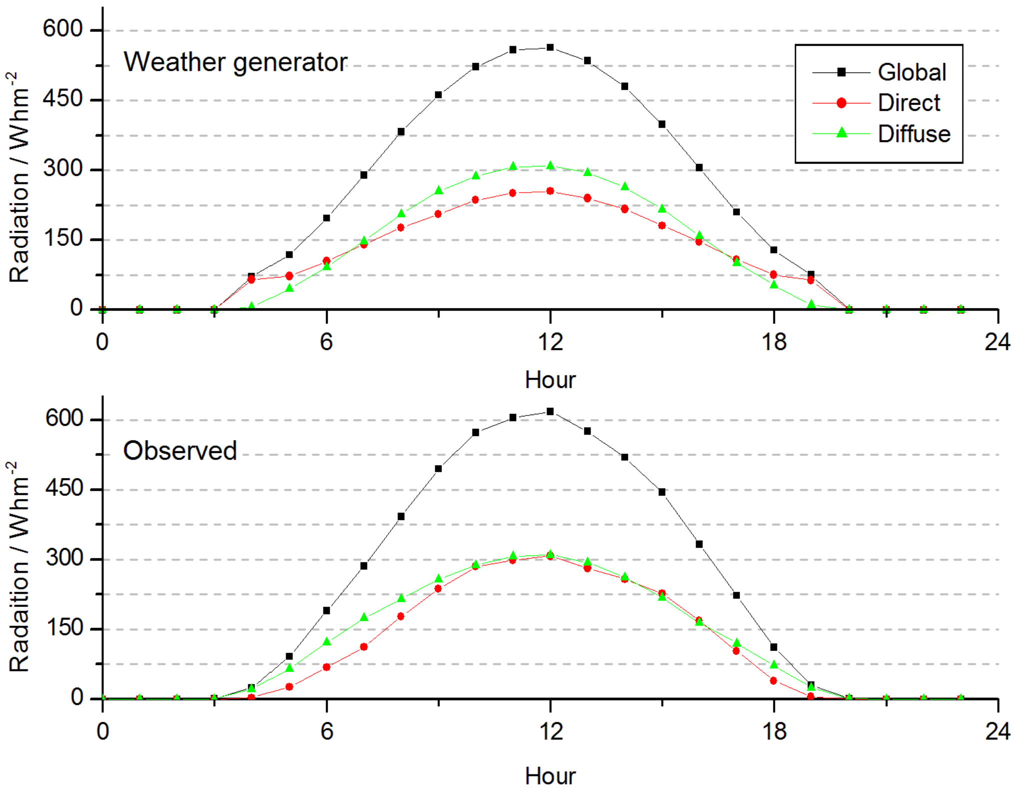


Figure 8. Hourly average global, direct and diffuse radiation from the weather generator and observations. All data is for Camborne and the month of June.

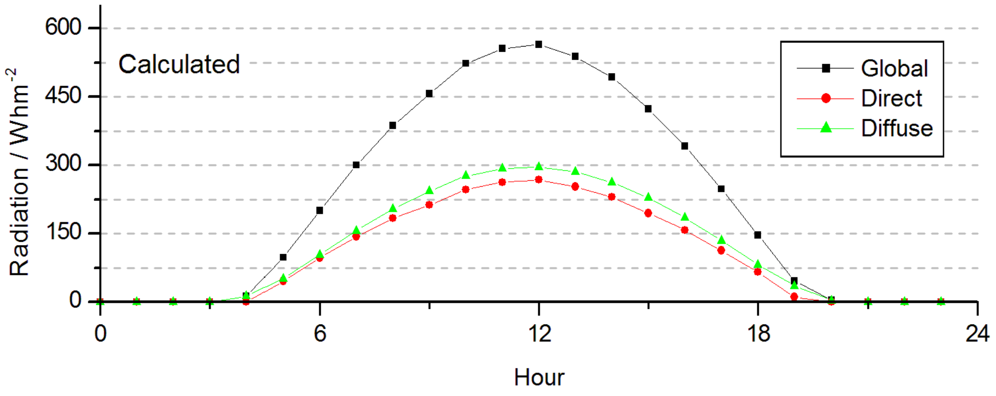


Figure 9. Hourly average global, direct and diffuse radiation from calculations using the weather generator and the cloud radiation model. All data is for Camborne and the month of June.

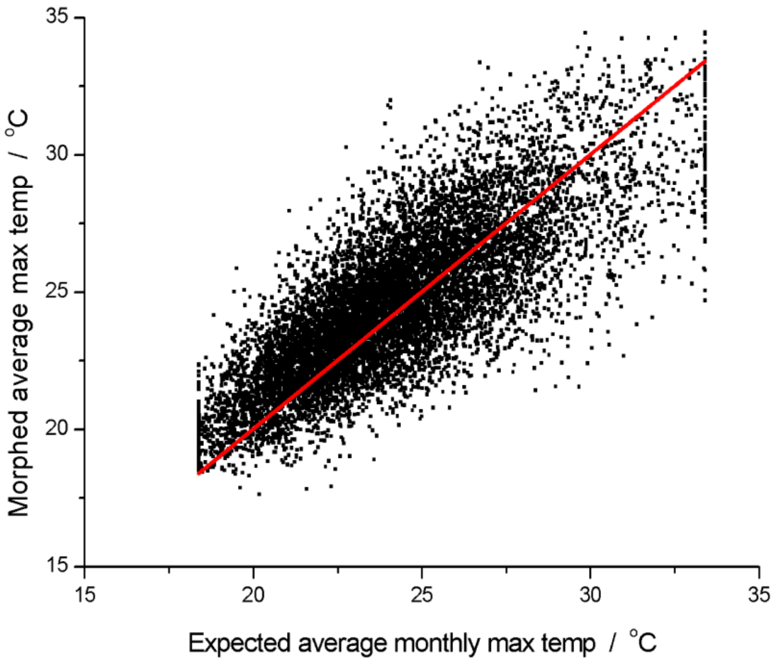


Figure 10. Graph showing morphed maximum temperatures against expected absolute maximum temperatures for the 2080's A1FI scenario for Plymouth. The line shows the expected result where the morphed average max temperature equals the expected average monthly max temperature.

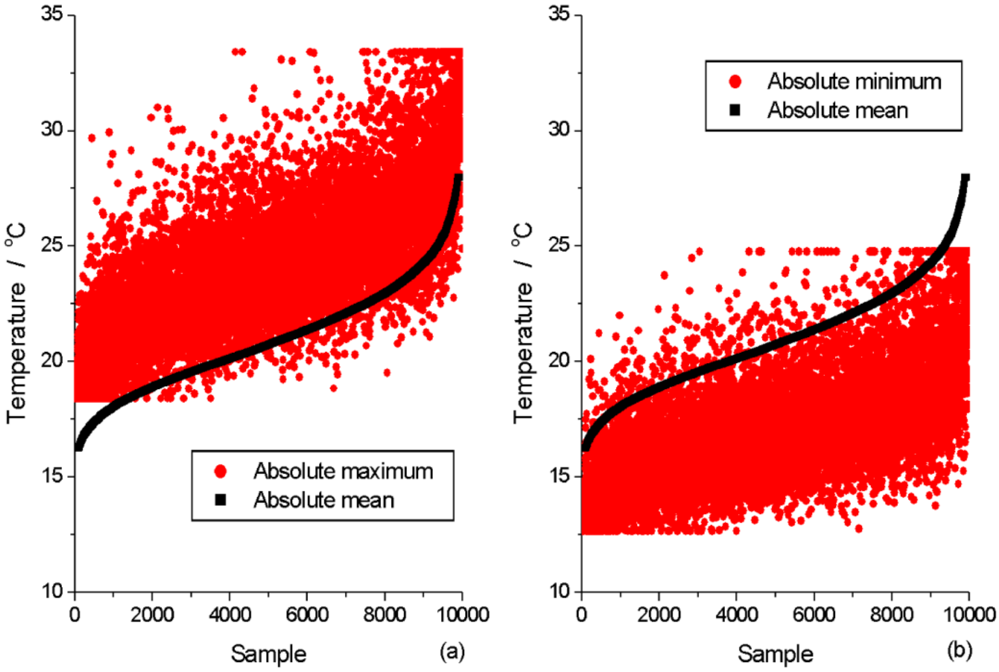


Figure 11. Graphs showing scatter plots of (a) the absolute maximum temperature and absolute mean temperature and (b) the absolute minimum temperature and absolute mean temperature for all samples for the 2080s A1FI scenario for Plymouth